Mem. S.A.It. Vol. 79, 3
Memorie della

The Peculiar Horizontal Branch Morphology of the Galactic Globular Clusters NGC 6388 and NGC 6441

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Abstract. I present multiband optical and UV Hubble Space Telescope photometry of the two Galactic globular clusters NGC 6388 and NGC 6441, in order to investigate the nature of the physical mechanism(s) responsible for the existence of an extended blue tail and of a slope in the horizontal branch. Further evidence that the horizontal branch tilt cannot be interpreted as an effect of differential reddening is provided, while I show that a possible solution of the puzzle is to assume that a small fraction of the stellar population in the two clusters is strongly helium enriched (Y∼0.40 in NGC 6388 and Y∼0.35 in NGC 6441).

Key words. Stars: horizontal-branch – Ultraviolet: stars – Globular cluster: individual (NGC 6388, NGC 6441)

1. Introduction

This work is part of an HST project devoted to study some globular clusters (namely NGC 6388, NGC 6441, NGC 6273 and NGC 5986), that show an extended horizontal branch (HB). In this paper I present the results for NGC 6388 and NGC 6441, while the results for the other two clusters will be published in a later paper.

The data are a merge of optical and UV observations, both collected with the WFPC2@HST. The optical data (in the filters F439W and F555W) are part of the previous Galactic Globular Clusters (GGCs) survey obtained from Piotto et al. 2002. The UV data represent an extension of the original F439W-F555W vs. F555W CMDs published by Rich et al. (1997) and Piotto et al. (2002). Because of the strong bolometric correction and temperature insensitivity, the optical data are not as useful in the study of the hottest HB stars, which can be better studied instead with the UV observations.

NGC 6388 and NGC 6441 are peculiar for several reasons:

- both clusters show not only the red HB, characteristic of metal-rich GCs as 47 Tuc ([Fe/H]= −0.76, Harris 1996) but also a quite extended blue HB.
- the mean HB brightness at the top of the blue HB tail is roughly 0.5 magnitudes brighter in the F555W band than the red HB portion, which appears significantly sloped as well. This slope, as pointed out in Sweigart & Catelan 1998 is not present in the theoretical models, and is difficult to explain (see also the discussion in Raimondo et al. 2002).

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Table 1. Fundamental parameters of NGC 6388 and NGC 6441[1].

	NGC 6388	NGC 6441
l	345.56	-353.53
b	-6.74	-5.01
$d_{\odot}$	10.0	11.7
[Fe/H]	-0.60	-0.53
$E(B-V)$	0.37	0.47

In an attempt to interpret the occurrence of the blue tail along the HB as well as of its tilted morphology, many non-canonical scenarios and/or observational effects have been suggested, as for example the initial He abundance, a spread in metallicity, differential reddening, rotation, etc. (see Catelan 2007 for a review).

The main parameters of NGC 6388 and NGC 6441, as given by Harris (1996, in the 2003 revision), are summarized in Table 1. The data come from HST/WFPC2 observations; in all cases, the PC camera was centered on the cluster center. The photometric reduction was carried out using the DAOPHOTII/ALLFRAME package (Stetson 1987, 1994). For more details about the data reduction see Busso et al. 2007.

2. The color-magnitude diagrams

In Fig. 1 the optical and UV band CMDs for both clusters are shown. The most relevant, common properties of these two clusters are the occurrence of an extended HB, and the tilt of the HB, as explained before. However, the HB morphology in the optical CMDs show also some differences: the blue HB appears more populated and extended in NGC 6388 than in NGC 6441; in the CMD of NGC 6441 there is a gap at $F555W \approx 18.5$; no such gap is visible in the HB of NGC 6388, which, instead seems to show a gap at $F555W \approx 19.8$; there is a large color spread at the hot end of the observed HB sequence, of the order of ~ 0.5 magnitudes in $F255W - F336W$, larger than the photometric errors (less than 0.1 magnitudes).

2.1. Differential reddening

Both clusters are affected by a sizeable amount of differential reddening (Piotto et al. 1997, Raimondo et al. 2002). In order to estimate the size of this effect, I divided the Planetary Camera field into 16 regions of 9×9 arcsec^2, and, for each region, the corresponding CMD has been plotted (not shown here, see Fig. 4 of Busso et al. 2007). A slope in the HB consistent with that observed for the whole sample is evident also in those regions where the narrowness of the red giant branch suggests that no strong residual differential reddening is present, forcing to conclude that the sloped HB is the consequence of an intrinsic property of the HB stars in NGC 6388 and NGC 6441 and it is not caused by differential reddening.

2.2. Comparison with the models

The observations were compared with Zero Age Horizontal Branch (ZAHB) models provided by Pietrinferni et al. (2006), supplemented by additional computations performed for this specific project, with a metallicity Z=0.008 and He contents Y=0.256 and an age of about 13Gyr. The reddening and distance modulus values adopted are those for which ZAHB models with the canonical Y=0.256 best fit the empirical distribution of the red HB clump in the (F336W-F439W, F439W) CMD (see Fig. 2), i.e. $E(F439W - F555W)$=0.45 and $(m - M)_{F555W}$=16.65 for NGC 6388, while for NGC 6441 we adopt $E(F439W - F555W)$=0.48 and $(m - M)_{F555W}$=17.4. This arbitrary choice was adopted for the sake of consistency with previous works and because cool ZAHB models should be more reliable than hotter ZAHB models (T_{eff} larger than about 10.000K), since they are not affected by diffusive processes.

Figure 3 shows a comparison, in the various photometric planes, between the ZAHB models and the HB sequences of NGC 6388

[1] l and b are respectively galactic longitude and latitude (in degrees), $d_{\odot}$ is the distance from the Sun (in Kpc), [Fe/H] is the metallicity, and $E(B-V)$ is the reddening (from the latest version of the Harris 1996 catalog).

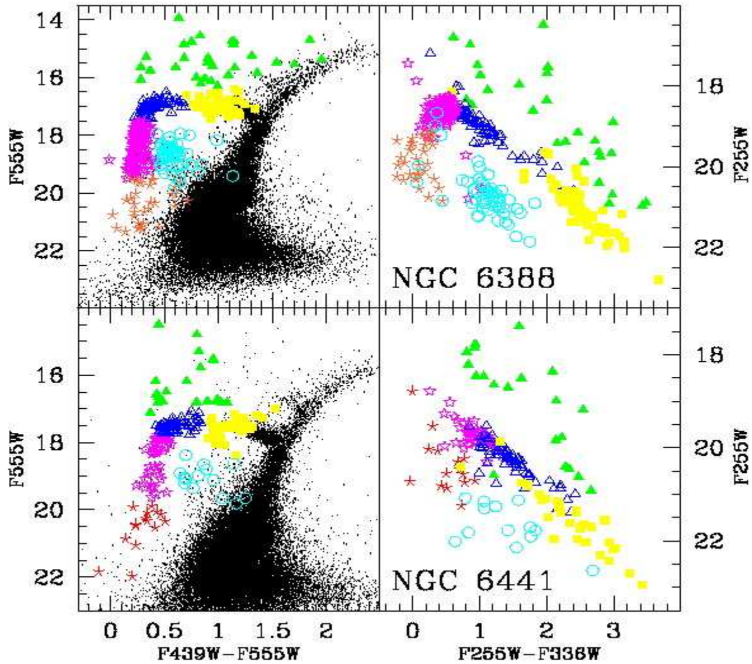

Fig. 1. Optical and UV CMDs for NGC 6388 (upper panels) and NGC 6441 (lower panels). The different symbols refer to the same group of stars appearing both in the optical and UV CMD: filled squares indicate the red HB, open triangles the blue HB, open stars the extended blue HB tail, the green triangles the post HB, the open circle the blue stragglers candidates, and the asterisks are the blue hook candidates.

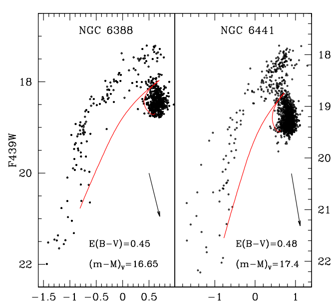

Fig. 2. (F336W-F439W, F439W) CMD of NGC 6388 and NGC 6441. The reddening and distance modulus values determined by best fitting in this diagram the red clump with the canonical ZAHB models (solid line) for $Y = 0.256$ are labeled. These canonical ZAHB models are plotted by using a solid line.

and NGC 6441. The ZAHB with canonical helium abundance Y=0.256 is plotted in the CMD with a red line. The comparison between theory and observations clearly shows that it is not possible to have an overall fit of the entire HB: a good fit of the red HB do not allow a good fit for the blue part, and vice versa. The striking evidence is that this is true for all combinations of colors and magnitudes, which raises the suspicion that there must be a real mismatch between the canonical ZAHB models and the observed HBs for both clusters. Fig. 3 shows also that the models with canonical Y=0.256 are not able to reproduce the color of the hottest HB stars in the CMD. This empirical finding could be interpreted as evidence that the effective temperature of these stars is significantly higher than that of the hottest HB models. This occurrence is evident for NGC 6388, but much less clear

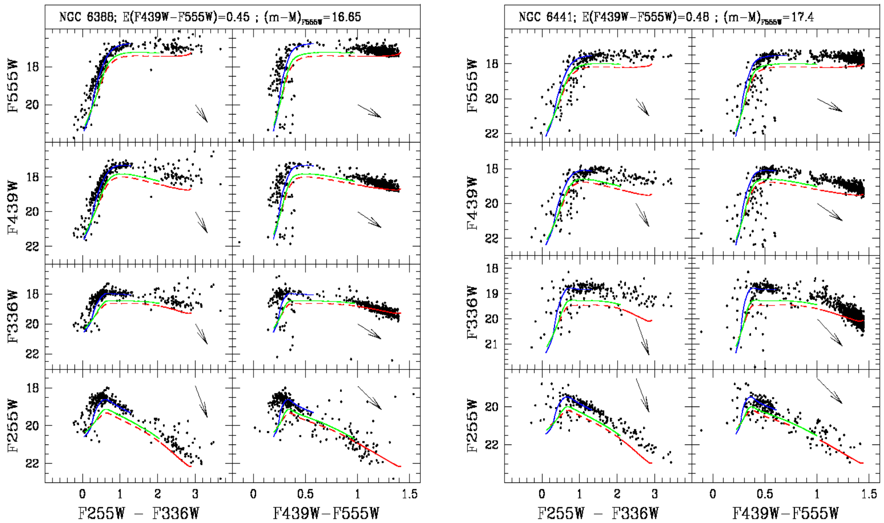

Fig. 3. Top panel: the HBs of NGC 6388 in different photometric planes. The observations are compared with theoretical models for a canonical Y=0.256 (lower red line), for Y=0.30 (middle green line), and for Y=0.40 (top blue line). The shifts applied to the stellar models for the adopted distance modulus and mean reddening are labeled in the figure, and they have been fixed according to the (arbitrary) choice of imposing a best fit between models and the lower envelope of the red HB portion in the (F336W-F439W, F439W) CMD (see Fig. 2). The arrows represent the reddening vector in the different photometric planes. Bottom panel: as in the top panel, but for NGC 6441.

in NGC 6441, which is not surprising, since we already noted that the latter has a much less populated and less extended blue HB. The presence of a possible gap, at $F555W \sim 19.8$, in the case of NGC 6388, just beyond the location of the hottest stars in the canonical models suggests that the stars observed beyond the gap could be blue hook stars, as those ones already observed by D'Cruz et al. (2000) in ω Centauri (NGC 5139) and by Brown et al. (2001) in NGC 2808.

2.3. A possible solution to the enigma

An interesting scenario that could help to solve the puzzle of the extended and tilted HBs of NGC 6388 and NGC 6441, has recently emerged from some quite unexpected results obtained for the Galactic GCs ω Cen and NGC 2808: both show multiple main sequence (Bedin et al. (2004), D'Antona et al. 2005, Piotto et al. 2007) which can be explained assuming that the various sequences are associated to stellar populations characterized by different initial He contents (D'Antona et al. 2005, Piotto et al. 2007).

The fact that, with ω Cen and NGC 2808, NGC 6388 and NGC 6441 are between the most massive GCs suggest to associate the anomalously blue and anomalously tilted HBs of NGC 6388 and NGC 6441 to a second generation of stars, strongly He-enriched by pollution from massive and/or intermediate-mass stars of the first star formation burst. A similar suggestion that the presence of a population with He enhancement can explain the anomalous HB of NGC 6388 and NGC 6441 has been recently made also by Caloi and D'Antona (2007). In order to verify this scenario additional sets of low-mass, He-burning models for a metallicity Z=0.008 and inital He contents equal to Y=0.30 and 0.40, were calculated. Fig. 3 shows a comparison between the observed CMDs and the theoretical models com-

puted for the various He contents, adopting the same reddenings and distance moduli. As already discussed, the models computed by assuming a canonical He content (Y=0.256) are not able to reproduce the blue HB. On the contrary, one can easily see that the ZAHB models corresponding to Y=0.40 are in good agreement with the observed distribution of blue HB stars of NGC 6388 in all of the CMDs (top of Fig. 3). The same kind of comparison, but for the case of NGC 6441, is performed in the bottom panels of Fig. 3. In this case, it is evident that the Y=0.40 ZAHB is slightly brighter than the observed distribution of blue HB stars. From the comparison between empirical data and the ZAHBs computed for various initial He contents, it appears that it is possible to reproduce the brightness of the blue HB star population by assuming a He content of the order of $Y \approx 0.35$, i.e. slightly lower than in NGC 6388. This fact is consistent with the observational evidence that the blue HB is less extended in NGC 6441 than in NGC 6388. The presence of two distinct stellar populations characterized by two different initial He contents can help in explaining the brightness difference between the red portion of the HB and the blue component. However, in order to explain the tilted morphology of the whole HB sequence one should also account for the presence of a spread in the He content at the level of about $\Delta Y \approx 0.05 - -0.06$ (see also Moehler & Sweigart 2006b, Caloi & D'Antona 2007).

Summarizing, the main peculiarities of the HBs are their extension to very hot temperatures, including (at least for NGC 6388) a number of blue hook candidates, and the presence of a tilt in the HB. Reddening and differential reddening may contribute to create a sloped HB, but neither of these effects is sufficient to explain the observed tilted HB. Canonical models are not able to reproduce the peculiar HBs of NGC 6388 and NGC 6441, while the presence of a He-rich stellar component allows to explain the observed blue HsB and the fact that they are brighter than the red HB clump. The presence of a He spread between the 'canonical' value and $Y \sim 0.35 - 0.40$ allows to explain the observed upward slope of the HB in both clusters.

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